Decarbonization at Nucor Seattle using Tallman Supersonic Carbon Injectors (TSCi™)

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INTRODUCTION

As one of the largest industrial consumers of fossil coal and a top-ranking industrial CO_2 emitter, the steelmaking industry has made decarbonization a central focus in its path to meeting global energy and climate goals. Steel production emits 2.6 gigatons of CO_2 per year, accounting for approximately 7% of total CO_2 emissions and 8% of global energy demand.[1]

While Electric Arc Furnaces (EAF) have the advantage of lower emissions due to their scrap charges as opposed to blast furnace iron, there remains an opportunity to optimize the consumption and efficiency of direct sources of carbon, leading to an immediate reduction in greenhouse gas (GHG) emissions.

Nucor Corporation has committed to a 35% combined reduction in steel mill scope 1 and scope 2 GHG intensity by 2030. This goal will take Nucor's steel mill CO_2 emissions down to 77% less than today's global steelmaking average.[2]

Nucor Steel Seattle installed and commissioned the Tallman Supersonic Carbon Injectors (TSCi™) for use in their 110-ton EAF located in Seattle, WA. The primary aim of this installation was to reduce total carbon input into the EAF, thereby realizing improved efficiency, significant cost savings, and supporting the Nucor corporate goal of reducing GHG emissions.

The TSCi™ is a patented particle injector designed to improve delivery of material to the EAF. Using this method, savings at Nucor Seattle were achieved by reducing the amount of total carbon (both charge and injection carbon) in each heat while maintaining or improving foamy slag practice. As well, significant energy savings were realized as a result of improved carbon injection efficiency.

DISCUSSION

Carbon in an EAF

Direct carbon sources are of great importance in an EAF for both their energy input and for slag foaming. Figure 1 shows a diagram of carbon input and direct emissions in an EAF. Solid carbon sources are used in the EAF in two ways: charge carbon, which serves as an energy input and to carburize the bath, and injection carbon, which reacts with the FeO – generated by the injection of oxygen – to form CO bubbles to foam the slag. While these carbon sources play an important role in an EAF, they contribute to around 40 to 70% of the direct CO_2 emissions of the electric steelmaking process.[3] With that in mind, one of the most direct methods to cut CO_2 emissions is to directly reduce the total carbon input into the EAF. This, however, must be accomplished using a method that does not negatively affect metallurgical and process results.

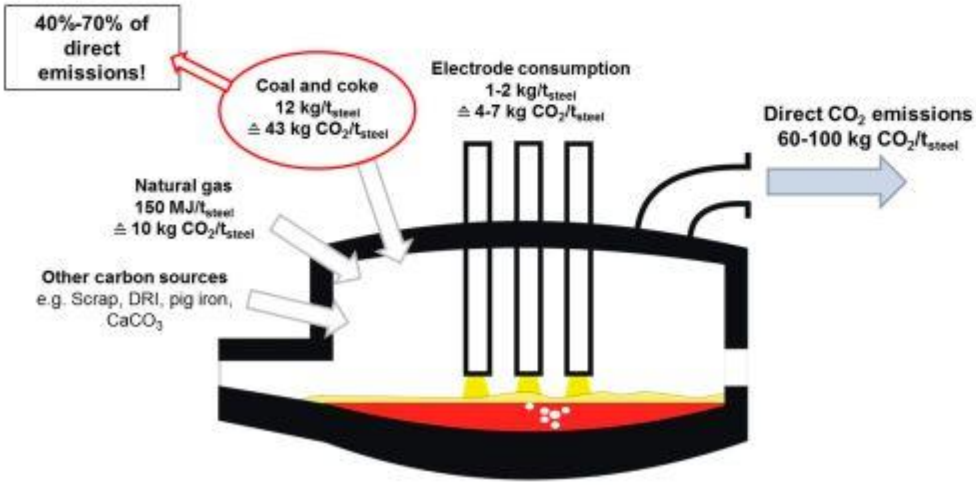

Figure 1: CO_2 emissions of a typical EAF[3]

Standard injection systems deliver carbon to the EAF using high pressure air, where the material is injected through a straight lance pipe or oxy-fuel burner. Finer carbon particles (less than 2mm) have a higher surface/volume ratio, making them more reactive and thus better at foaming the slag. The challenge, particularly with fine carbon particles, is that a significant portion – in the range of 50% – is lost to the off-gas system, burns in the freeboard or in the flame of the oxy-fuel burner and never reaches the slag/metal interface. On the other hand, large particles (barley size) have enough momentum to reach the slag/metal interface but tend to float and burn on the surface rather than react with the FeO.

In most cases, steelmakers must overcompensate these inefficiencies, and inject extra carbon to ensure enough reaches the slag/metal interface. Compounding the problem is that carbon blown on the top of the slag has the detrimental effect of collapsing the CO bubbles.[5] Also often ignored is the fact that anthracite coal contains siliceous ash that contributes to slag volume. This silica must be fluxed, creating a cycle of increased slag mass, energy consumption and metallic losses.[5]

Similarly, the steelmaker compensates for the inefficient injection of carbon by using charge carbon to recarburize the steel bath. Charge carbon is similarly inefficient, with inconsistent recovery ranging from 30 to 80%.[6] The charge carbon also has the detrimental effect of reducing the majority of the FeO in the slag carried over from the last heat, thus impeding the ability to foam the slag early in the heat. Some CO is generated with the reaction of the oxygen with the carbon in the bath, but as the carbon level reaches 0.1%, the generation of FeO increases. Thus, injection carbon is still required to reduce the FeO and foam the slag even with the use of ore-based metallics (OBM) made from green hydrogen.

Inefficiency in the current use of injection carbon and charge carbon can be overcome if fine (high surface/volume) carbon particles can be efficiently delivered to the slag/metal interface. Tallman Technologies Inc. has developed an injector designed to improve injection carbon delivery to the EAF by increasing material delivery efficiency using supersonic methods. It is a proven technology with installations at numerous steelmaking facilities around the world.[7] The Tallman Supersonic Carbon injector (TSCi™) is suitable for injecting very fine, low density material including biochar, plastics, and lime. Many if not all the earlier trials on injecting low density biomass and plastics need to be revisited considering the inefficient delivery method used during these trials.[8]

The delivery of material though the straight pipe injectors is limited by the pressure difference between the injection system and the EAF atmosphere, as well as the velocity of the conveying transport air. Figure 2 shows a typical example of carbon being injected into an EAF.[7] The shape of the carbon stream increases in size because of the pressure difference between the conveying stream and the EAF atmosphere. As a result, the delivery efficiency of carbon is reduced. By this method, a significant portion of injected material, particularly the smaller, less dense particles, are lost to the fume system, combusted in the freeboard, or lie on top of the slag. Simply increasing the air pressure will not greatly improve the delivery of the carbon to the slag/metal interface and will increase the wear of the carbon conveying piping.

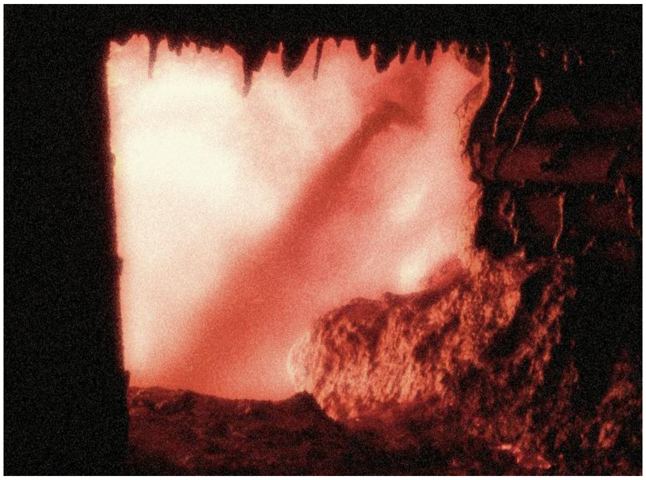

Figure 2: Injection of Carbonaceous Material into EAF using Straight Pipe Method

Pre-Installation Operation at Nucor Seattle

Prior to the installation of the TSCi™, Nucor Seattle injected calcified petroleum coke fines using 'dense phase' conveying through three 2-¼" ID straight pipe carbon injectors. Typical injection carbon consumption was approximately 1,800 pounds per heat, or 15 lbs./t. Injection carbon is stored in two pressure vessels. Compressed air forces the carbon into the conveying lines for delivery to the EAF. The conveying system uses butterfly valves at the outlet of each pressure vessel to control the flow of carbon to the conveying lines. The quantity of carbon delivered to the EAF is controlled by the amount of time the butterfly valves remain in the open position. Setpoints for the pressure vessel and carbon conveying line were set at 45psi and 60psi respectively. Like most EAF shops, carbon efficiency was not a primary focus and therefore the calibration/accuracy of the carbon conveying system had not been a main consideration.

Nucor Seattle maintained a charge carbon practice commonly observed by the authors in numerous other EAF shops. Nucor Seattle uses a mixture of crushed anodes sized ½" and down, and 2" x 3" anthracite. The charge carbon is loaded into the bucket from a bulk silo along with the scrap and is charged into the furnace. Typically, Nucor Seattle would start with a base amount of charge carbon in the range of 1000 to 1200 pounds and adjust based on the carbon levels in the furnace at tap, provided by the CELOX readings. At the time of commissioning of the TSCi™ technology, 1200 pounds of charge carbon was added per heat in the charge bucket. Nucor Seattle charges 3 buckets per heat and charge carbon additions alternated between the first and second charge depending on which bucket comes off the #1 transfer car, as the top feed delivery system is located above the #1 track.

Tallman Supersonic Carbon Injector (TSCi™)

A typical TSCi™ is shown in Figure 3. The injection carbon enters the Carbon Chamber and is accelerated down the Barrel by the supersonic transport air. The supersonic transport air also creates a venturi effect that draws carbon into the Carbon Chamber.

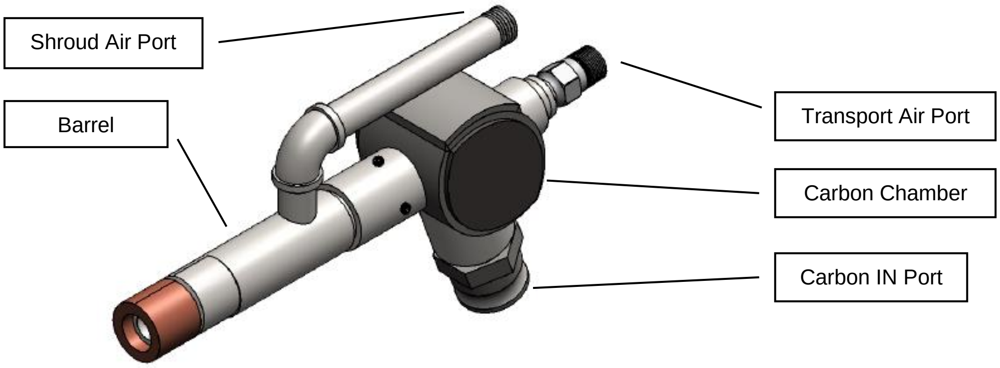

Figure 3: TSCi™ – Operational Schematic

The carbon, upon exiting the injector, is shrouded by an annular supersonic shroud jet. The annular supersonic shroud jet prevents the spread of injection carbon from the stream. Figure 4 shows a comparison between a standard injection system and the TSCi™. Injected material travels 6-8 feet with little degradation of the stream. The life of the TSCi™ is a function of the hardness of the carbon, the velocity of the carbon as it enters the carbon chamber, and the total amount of carbon conveyed through the TSCi™.

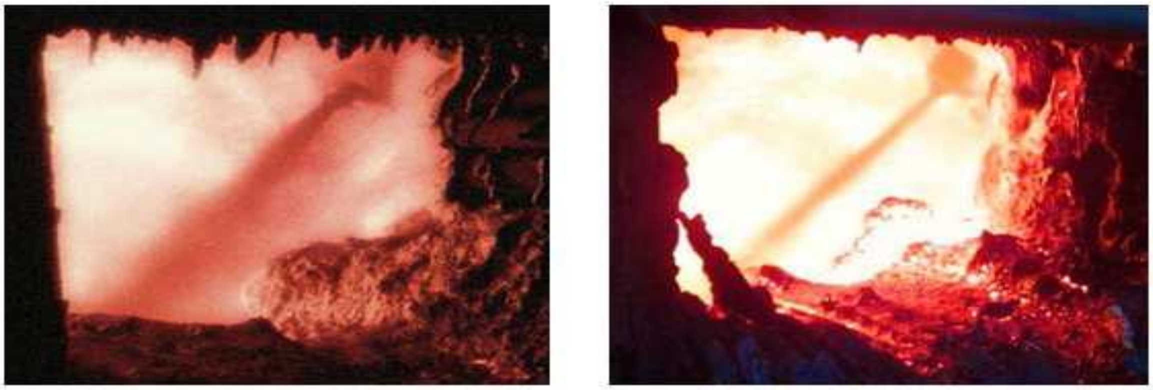

Figure 4: Straight Pipe Carbon Injector (Left) versus TSCI™

Installation at Nucor Seattle

Two (2) TSCi™ were installed at Nucor Seattle in position #1 and #2 in March 2021. Position #3 remains a straight pipe injector as Nucor Seattle does not have the compressed air availability to install a third TSCi™. Plans are to convert #3 to a TSCi™ after the purchase of an additional compressor to serve the injectors. Details of the installation can be seen in Figure 5.

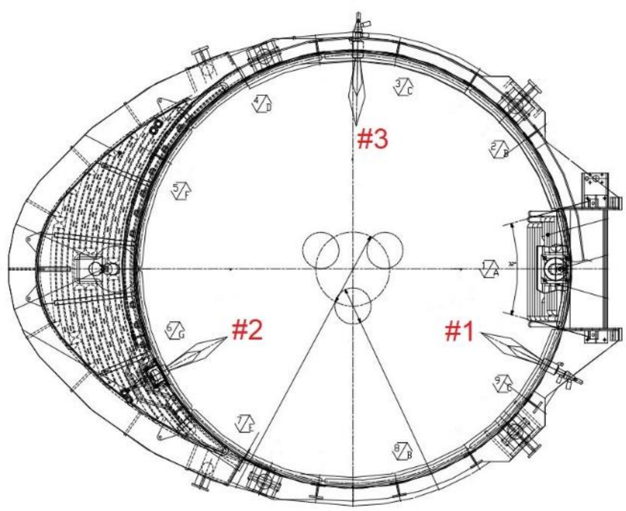

Figure 5: Top view of EAF at Nucor Seattle

Nucor Seattle injects calcified petroleum coke baghouse fines supplied from a local oil refinery with a typical composition shown in Table 1. The injection carbon consists of 5 to 30 μm size particles. The injection carbon is similar in consistency of that of printer toner.[9] The use of such ultra-fine/low density injection carbon is not common in North American and is the finest powder injected using the TSCi™ to date.

Sulfur, wt.%	2.8-3.4
Ash, wt. %	<0.5
Volatile Matter, wt.%	<0.5
Moisture, wt.%	<0.5
Fixed Carbon, wt.%	>95%

Table 1: Typical Petroleum Coke Chemistry at Nucor Seattle

During commissioning, adjustments had to be made to the carbon conveying system to compensate for the venturi effect created by the supersonic transport air. When the injectors were initially installed, the pressure vessel was set at 45 psi and the conveying line pressure at 60psi. At these pressure settings only a minimal amount of carbon was able to be conveyed to the TSCi™. After some experimentation, the tank pressure was reduced to 35psi and the conveying line pressure to 25psi. Lowering these pressures was critical to creating a stable, consistent flow of carbon through the carbon conveying system to the TSCi™. This lower pressure has the added maintenance benefit of improving the life of the carbon conveying piping while also reducing compressed air usage

The shroud and transport air flow are controlled by a pressure regulation system that is mounted near the EAF. The pressure regulators are initially set slightly higher than the design pressure of the TSCi™ to compensate for the pressure drop in the lines between the TSCi™ and the pressure regulation system. For commissioning purposes there is also a pressure gauge installed on the shroud air inlet on the TSCi™. The pressures are set to achieve the designed flow rate. The coherency of the carbon jet is affected by the shroud air pressure, transport air pressure, the conveying air pressure and flow rate, and the density/size/flow rate of the injection carbon. A final visual observation of the carbon stream is required. Fine adjustments are made to the air pressures to focus the carbon stream.

At Nucor Seattle supply air pressure requirements maxed at around 80 psi and thus the carbon stream was not fully optimized. While the carbon stream with the TSCi™ is a major improvement, in future, when the dedicated air compressor is purchased, the carbon stream will be further optimized.

During commission, charge carbon input was reduced in stages along with reductions in injection carbon. Initially charge carbon was reduced from 1200 pounds to 800 pounds coupled with an injection carbon flow rate reduction of 25%. Charge carbon and injection carbon were further reduced during commissioning while monitoring metallurgical and process results.

The baseline data and results for Nucor Seattle for charge carbon consumption are shown in Figure 6. The baseline data shows an average value (calculated as average consumption per month) from Jan 2019 to Feb 2021 of 10.97 lbs./ton. Following installation of the TSCi™ and the actions taken to stabilize the process, the average consumption for charge carbon reduced to 3.61 lbs./ton. This corresponds to a decrease of 67%.

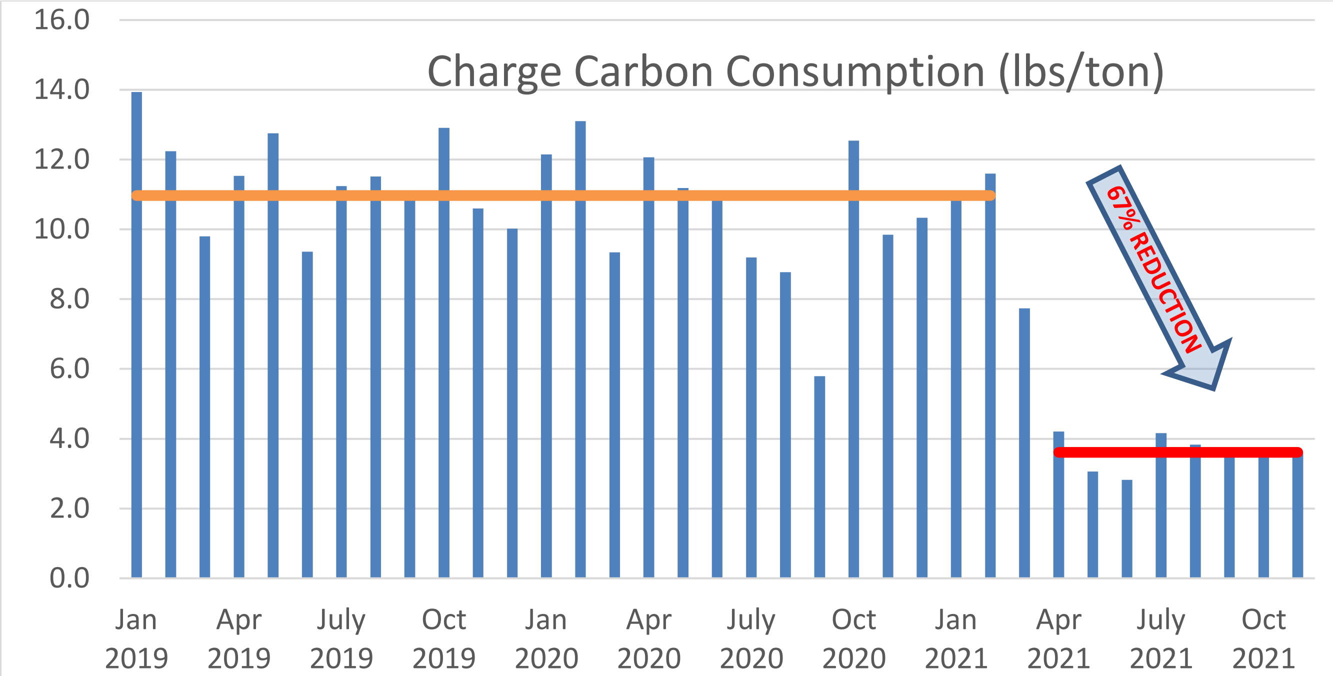

Figure 6: Charge Carbon Consumption at Nucor Seattle vs. Established Baseline

The baseline data and results for Nucor Seattle for injection carbon consumption are shown in Figure 7. The baseline data shows an average value (calculated as average consumption per month) from Jan 2019 to Feb 2021 of 14.39 lbs./ton. Following installation of the TSCi™ and the actions taken to stabilize the process, the average consumption for charge carbon reduced to 9.99 lbs./ton. This corresponds to a decrease of 30.6%.

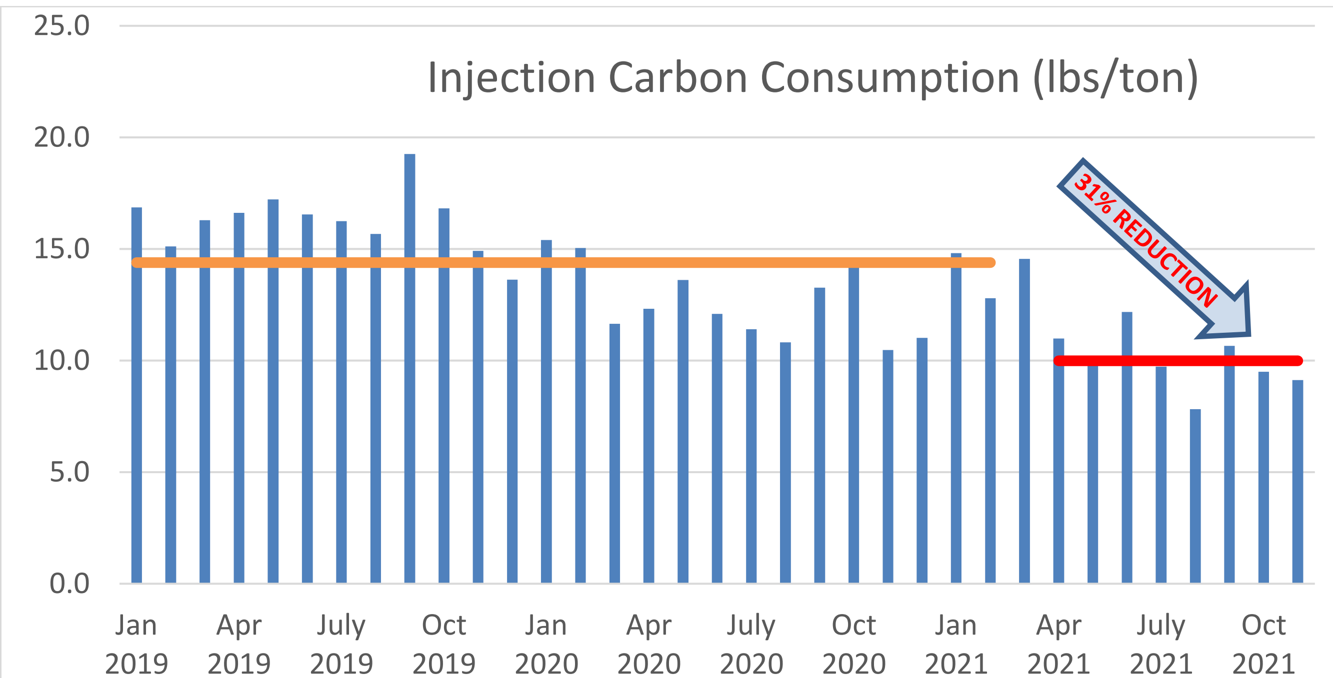

Figure 7: Injection Carbon Consumption at Nucor Seattle vs. Established Baseline

Figure 8 shows the total carbon reduction at Nucor Seattle compared to the established baseline. Following the installation of the TSCi™ and the actions taken to stabilize the process, the average total carbon consumption reduced from 25.35 lbs./ton to 13.60 lbs./ton. This corresponds to a total decrease of 46.3%.

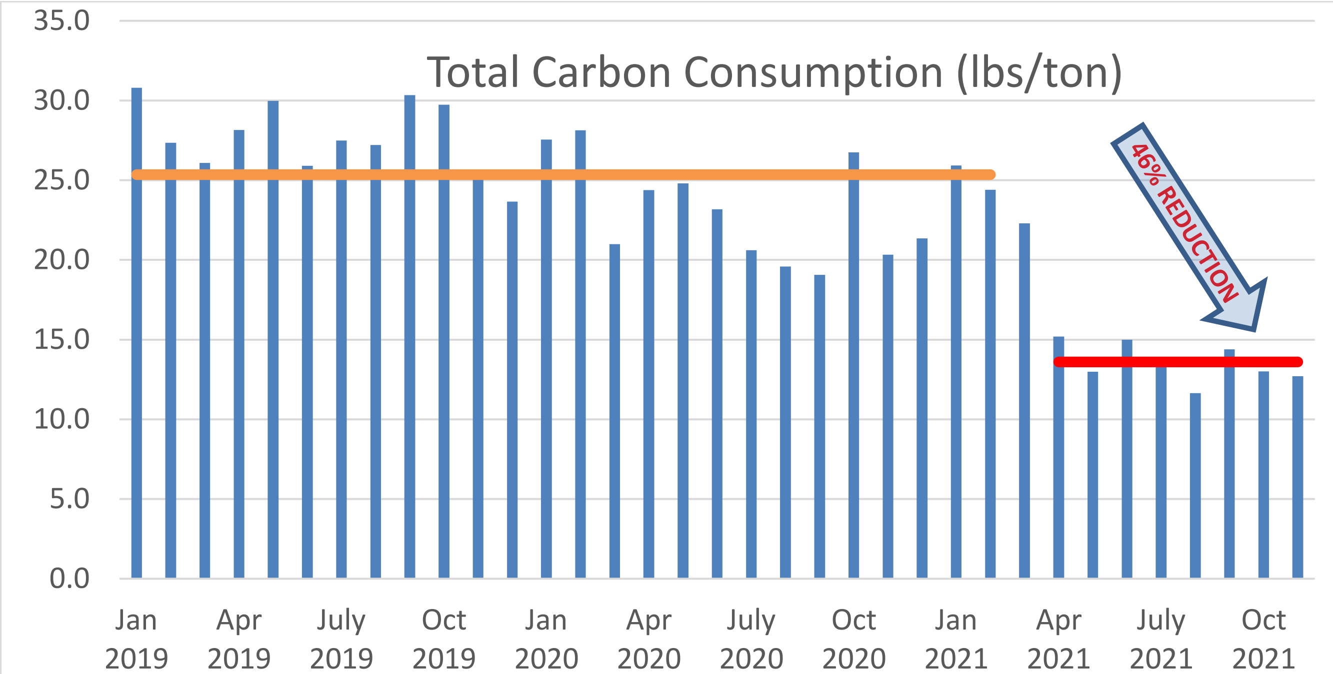

Figure 8: Total Carbon Consumption at Nucor Seattle vs. Established Baseline

With the TSCi™, it was possible to efficiently deliver injection carbon to the slag and slag/metal interface, reducing losses and allowing for a reduction in the total carbon consumption in the EAF.

Reduction of total carbon is not the only direct benefit of improved carbon injection efficiency. As shown in Figure 9 and 10 Nucor Seattle realized significant improvements in their power on time and electrical energy. High Energy Program (HEP) power on time was reduced by 1.3 minutes and HEP kWh per cast ton reduced by 3.3%, making the HEP as efficient as the Low Energy Program (LEP) with standard straight pipe injectors installed.

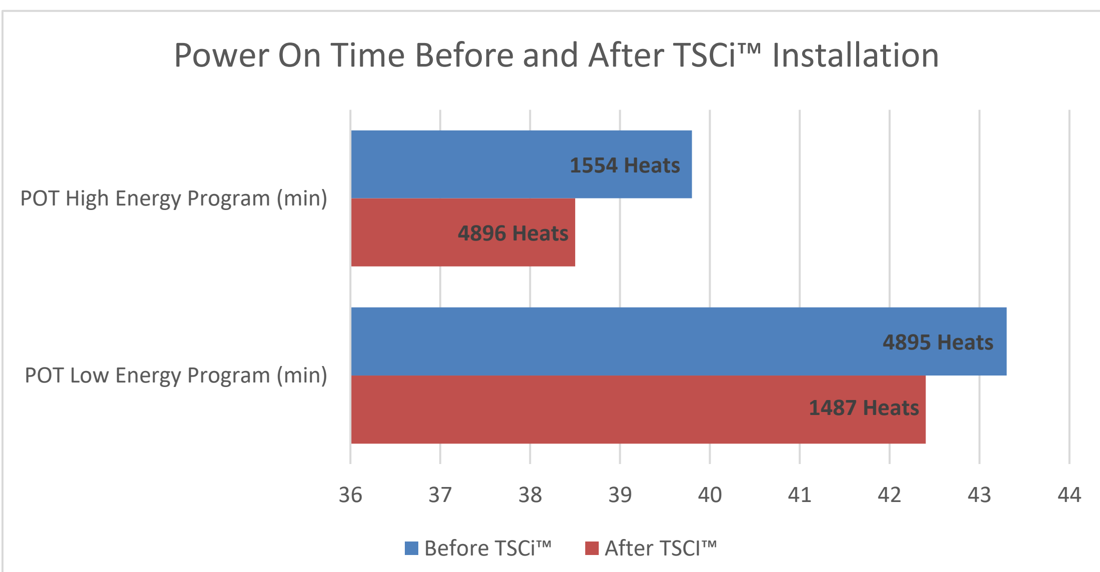

Figure 9: Power on Time Before and After TSCi™ Installation

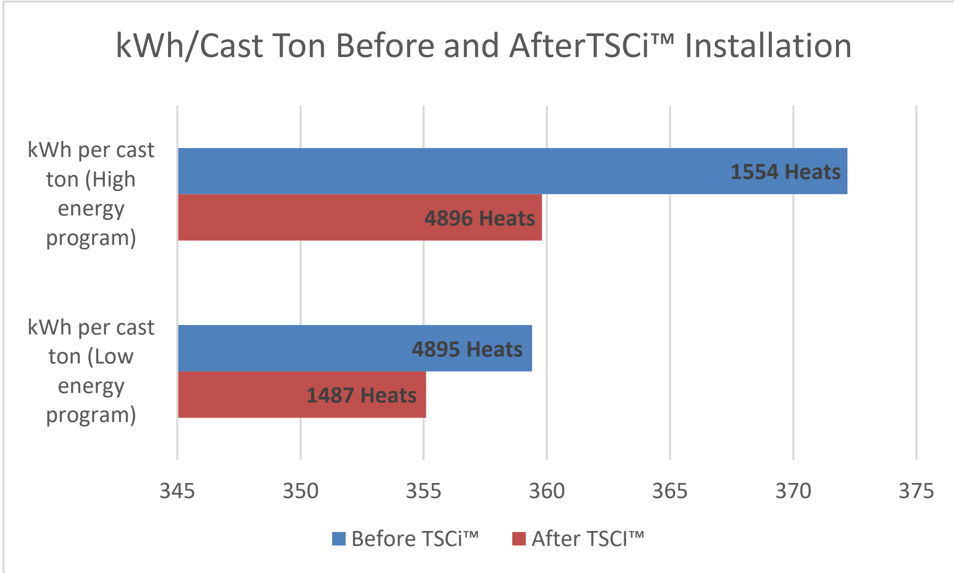

Figure 10: kWh per Cast Ton Before and After TSCi™ Installation

It should be noted that shortly after the TSCi™ installation, Nucor Seattle switched to a HEP due to the sharp increase in steel pricing, explaining the small baseline for the HEP before the TSCi™ installation and the low sample size of the LEP after the TSCi™ installation.

The melt-in carbon and the slag FeO levels were essentially the same as shown in Table 2, despite the fact that 46% less carbon was added to the furnace. More data would need to be collected and analyzed to make a direct correlation to improved carbon injection efficiency on these KPI's.

	Before TSCi	**After TSCi**
Melt In Carbon (%)	**0.09**	**0.10**
% FeO in Slag	**31.3**	**29.6**

Table 2: Melt in Carbon and Slag FeO Before and After TSCi™ Installation

As indicated in Table 1, the sulfur content of Nucor Steel's PET coke ranges from 2.8 to 3.4%. Even with more efficient delivery of carbon to the slag/metal interface, there is no increase in S pick-up as shown in Figure 11.

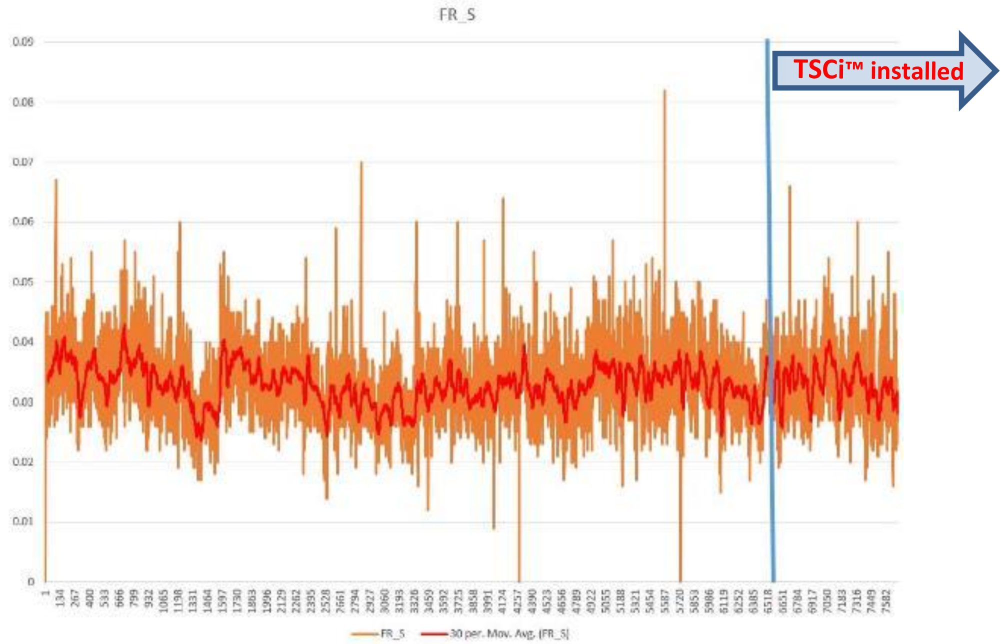

Figure 11: Sulphur Levels at Nucor Seattle

While the entirety of this improvement cannot be attributed to improved efficiency of injection carbon, it is well known that improving slag foaming will result in improved process indicators in the EAF. The results when using the TSCi™ technology at Nucor Seattle also validate the energy and carbon savings that were reported and presented in an earlier paper with regards to the installation at Gerdau Monroe.[7]

Future Work

As discussed, there is still room for Nucor Seattle to further optimize the TSCi™. A dedicated air compressor will allow for additional air capacity to further focus the carbon stream and to replace the last straight pipe injector with a third TSCi™. Replacing the butterfly valves with rotary valves will give Nucor Seattle more control over the carbon feed rate and allow for the carbon consumption to be further dialed back. With the successful injection of very fine carbon particles, Nucor is scheduling trials for injection of biochar, (potentially plastics and other green carbon sources), paving the way for further CO_2 reductions

Conclusions

The TSCi™ allows for the injection of fine carbon particles to travel farther into the EAF with increased momentum as compared to a standard 'straight pipe' injection.

Using the Tallman Supersonic Carbon injector (TSCi™) improves carbon injection efficiency and improves slag foaming. Results at Nucor Seattle showed a reduction in charge carbon consumption of approximately 67% along with a reduction in injection carbon of approximately 30.6% compared to established baseline. Reduced electrical consumption and power on times have also been achieved. Total carbon reduction of almost 1500 lbs. per heat equates to a more than 2.6-ton reduction in CO_2 emissions per heat or 18,800 tons of CO_2 annually. The proven ability to inject fine, low-density particles opens the door for the use of "green" injectable materials that have the potential for even better slag foaming. Nucor Seattle is well on its way in supporting the Nucor corporate goal of reducing CO_2 emissions across all its EAF steelmaking facilities.

REFERENCES

1. International Energy Agency. “Iron and Steel Technology Roadmap Towards more sustainable steelmaking,” *IEA Publications*, France, 2020, pp. 11-16.
2. Nucor. “Greenhouse Gas Reduction Target Strategy,” 2021. Available online: https://www.nucor.com /greenhouse-gas-reduction-target-strategy/#:~:text=Nucor%20is%20committing %20to%20a,than% 20today's %20global%20steelmaking%20average.
3. Echterhof, T., “Review on the Use of Alternative Carbon Sources in EAF Steelmaking,” *Metals*, Vol. 11, No. 222, January 2021.
4. Ozturk, B., and Fruehan, R.J., “ Effect of Temperature on Slag Foaming,” *Metallic Material Journal,* Vol. 26B, 1086-1088.
5. Cotchen, K.J., and Voss, Z., “Carbon and Oxygen Usage in the EAF – Is More Always Better,” *Iron & Steel Technology*, January 2020.
6. Pretorius, E.; Oltmann, H.; and Jones, J., “EAF Fundamentals”, *LWB Refractories Process Technology Group.*
7. Bruch, R.; Gillgrass, S.; and Strelbisky, M., “Results at Gerdau Monroe Using Tallman Supersonic Injection System,” *AISTech Conference Proceedings*, 2017.
8. Baracchini, L.B.G., et al., “ Sustainable EAF Steel Production (GREENEAF),” *European Commission Research Fund for Coal and Steel*, 2013.
9. Microtrac MRB. “Static Image Analysis of Toner Particles,” 2022. Available online: https://www.microtrac. com/applications/toner-particles/#:~:text=Toner%20is%20a%20very%20fine,oxides%20and%20 various%20 auxiliary%20substa